OPTICAL WAVEGUIDE WITH MULTIPLE CORE LAYERS AND METHOD OF FABRICATION THEREOF

FIELD OF THE INVENTION

This invention relates to an optical waveguide with multiple core layers and a method of fabrication thereof.

In particular, the invention relates to a doped planar waveguide with multiple core layers and which includes both active and passive components and to a method of fabricating a planar waveguide for an optical circuit in which the core is composed of layers of different materials.

BACKGROUND OF THE INVENTION

Planar waveguides can be passive devices or can include active components; for example, modulators, couplers, and switches. Planar waveguides incorporating active components are extremely advantageous as they can be used to provide integrated

optic packages which can serve as complete transmitting modules with, for example, components for amplitude or phase modulation, or multiplexing in an optical communication network.

Rare earth doped fibre amplifiers, for example erbium or neodymium doped fibre amplifiers, are known to have several advantages in optical communication networks such as high gain, low noise, high power conversion efficiency and wide spectral bandwidth. The present invention seeks to provide the same advantages in planar rare earth doped waveguides and moreover to provide a laser waveguide amplifier which can be used, for example, in an optical communication network to amplify attenuated signals.

Planar waveguide technology is important in the fabrication of lasers and optical amplifiers due to the superior stability, compact geometry of planar waveguide technology. Also, active components, for example modulators, can be integrated into the planar device.

A variety of techniques, including flame hydrolysis deposition (FHD), sputtering, plasma enhanced chemical vapour deposition (CVD) and ion-exchange can be used in the fabrication of silica-based planar waveguides doped with rare-earth ions and which display laser characteristics.

In such laser amplifying waveguides, it is desirable to obtain a high concentration of rare earth ions in order to achieve very compact and efficient devices. However, high concentrations of rare earth ions in a waveguide layer with relatively low solubility can result in the formation of clusters of rare earth ions.

The interaction between the rare earth ions in such clusters quenches the excited state required for the lasing process and thus degrades the optical amplification provided by the waveguide.

Other complications arise in the fabrication of laser waveguides for applications which require single mode transmission, narrow spectral bandwidths, and/or precise control of the lasing wavelength depend critically on their cavity type. Laser waveguides which have butt-coupled mirrors on the waveguide ends or dielectric reflection mirrors are known in the art but suffer to a greater or lesser degree from certain disadvantages; for example, low spectral selectivity.

Bragg gratings incorporated in a waveguide core can provide enhanced spectral selectivity. The fabrication of such gratings is affected by the host glass composition present in the waveguide core which determine the UV absorption band of the core material and thus its photosensitive properties. For example, if phosphorus is used as a core dopant ion it can alleviate the formation of rare earth ion clusters but has the disadvantage that it reduces the amount of absorption in the UV and thus reduces the photosensitivity of the core. If germanium is used as a core dopant ion it can increase the photosensitivity of the core but has the disadvantage of promoting rare earth cluster formation.

The introduction of a Bragg grating can be effected in a planar waveguide by a number of known methods which suffer to a greater or lesser degree from certain disadvantages. The invention provides an optical waveguide with multiple core layers which is suitable for forming a laser waveguide with a high degree of

spectral selectivity. The waveguide core combines two different types of silica based layers and these core layers obviate or mitigate the aforementioned disadvantages which arise when seeking to fabricate an in-core Bragg grating to enhance the spectral selectivity of the laser waveguide. The waveguide formed enables in-core Bragg grating formation at a range of UV wavelengths above 150 nm.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the invention there is provided an optical waveguide with multiple core layers comprising: a substrate; a waveguide core formed on said substrate; and an upper cladding layer embedding said waveguide core; wherein said waveguide core comprises a first core layer and a second core layer.

Preferably, the substrate comprises silicon and/or silica and/or sapphire.

Preferably, the substrate includes an intermediate layer. The intermediate layer may include a buffer layer formed on the substrate. The buffer layer may comprise a thermally oxidised layer of the substrate.

The intermediate layer may further include a lower cladding layer formed on said buffer layer.

Preferably, the thickness of the buffer layer is in the range 5 μm to 20 μm.

The second core layer may be formed on the first core layer and said first core layer may be formed on the substrate. Alternatively, the first core layer may be

formed on the second core layer and said second core layer may be formed on the substrate. A further first core layer may be formed on the second core layer such that the first core layer sandwiches the second core layer.

Preferably, the first core layer includes a dopant to permit the first core layer to exhibit a photosensitive response. The first core layer may include silica.

Preferably, the first core layer includes a germanium oxide and/or a boron oxide. The first core layer dopant may include dopant ions. Preferably, the first core layer dopant ions include tin and/or cerium and/or sodium.

The second core layer may include a dopant to induce amplification of an optical signal transmitted through said waveguide core. The second core layer may include silica. The second core layer may include a phosphorus oxide. The second core layer dopants may include dopant ions. The second core layer dopant may include a mobile dopant.

Preferably, the second core layer dopants include a rare earth and/or a heavy metal and/or compounds of these elements. More preferably, the rare earth is Erbium or Neodymium.

Preferably, the refractive indices of the first core layer and the second core layer are substantially equal.

Preferably, the refractive index of the waveguide core differs from that of the substrate by at least 0.05%.

Preferably, the thickness of the first core layer is in the range 0.2 μm to 30 μm.

Preferably, the thickness of the second core layer is in the range 0.2 μm to 30 μm.

Preferably, the width of the waveguide core lies in the range 0.4 μm to 60 μm.

The upper cladding layer and the lower cladding layer may comprise the same material. The refractive index of the substrate and the refractive index of the upper cladding layer may be substantially equal.

In accordance with a second aspect of the invention there is provided a method of fabricating a waveguide comprising the steps of: providing a substrate; forming a waveguide core on the substrate; and forming an upper cladding layer to embed the waveguide core, wherein the waveguide core is formed from a first core layer and a second core layer.

The formation of the substrate may include the formation of an intermediate layer formed on said substrate. The formation of the intermediate layer may include the formation of a buffer layer. The buffer layer may be formed by thermally oxidising the substrate.

The formation of the intermediate layer may further include the formation of a lower cladding layer formed on said buffer layer. The formation of the lower cladding layer may include doping said lower cladding layer with a dopant. The dopant may include dopant ions.

Preferably, the second core layer is formed on the first core layer and the first core layer is formed on the substrate. Alternatively, the first core layer may be formed on the second core layer and said second core layer may be formed on the substrate.

A further first core layer may be formed on the second core layer such that the first core layer sandwiches the second core layer.

The steps of forming any one of the substrate, first core layer, the second core layer, and the upper cladding layer may comprise the steps of:

depositing each layer; and

at least partially consolidating each layer.

Preferably, any one of the substrate, the first core layer, the second core layer and the upper cladding layer partially consolidated after deposition is fully consolidated with the full consolidation of any other of the first core layer, the second core layer or the upper cladding layer.

Preferably, the formation of the first core layer includes the doping of the first core layer with a dopant.

Preferably, the first core layer dopant permits the first core layer to exhibit a photosensitive response.

Preferably, the formation of the second core layer includes the doping of the second core layer with a dopant.

Preferably, the second core layer dopant induces amplification of an optical signal transmitted through

said waveguide core.

The formation of the substrate may include the doping of the substrate with a dopant. The dopant may include dopant ions.

Preferably, the substrate dopant includes a mobile dopant.

Preferably, said first core layer dopant ions include tin and/or cerium and/or sodium.

Preferably, said second core layer dopant ions include a rare earth and/or a heavy metal and/or compounds thereof.

Preferably, said rare earth is Erbium and/or Neodymium.

Preferably, the concentration of the first core layer dopant is selectively controlled during the formation of the first core layer and the concentration of the second core layer dopant is selectively controlled during the formation of the second core layer so that the refractive index of the first core layer and the refractive index of the second core layer are substantially equal.

Preferably, the concentrations of the first core layer dopant and second core layer dopant are controlled to give a refractive index for the waveguide core which differs from that of the substrate layer by at least 0.05%.

The lower cladding layer and said buffer layer may be formed substantially in the same step. At least one of the substrate, the first core layer, the second core

layer, and the upper cladding layer may be deposited by a Flame Hydrolysis Deposition process and/or Chemical Vapour Deposition process. The Chemical Vapour Deposition process may be a Low Pressure Chemical Vapour Deposition process or a Plasma Enhanced Chemical Vapour Deposition process.

Preferably, the consolidation is by fusing using a Flame Hydrolysis Deposition burner. Alternatively, the consolidation may be by fusing in a furnace.

The step of fusing the lower cladding layer and the step of fusing the first core layer and/or the second core layer may be performed simultaneously. The waveguide core may be formed from the first core layer and the second core layer using a dry etching technique and/or a photolithographic technique and/or a mechanical sawing process. The dry etching technique may comprise a reactive ion etching process and/or a plasma etching process and/or an ion milling process.

The waveguide core formed from the first core layer and the second core layer may be square or rectangular in cross-section.

In accordance with a third aspect of the invention there is provided a laser waveguide with multiple core layers comprising a waveguide according to the first aspect of the invention, the laser waveguide further comprising:

at least one grating formed in said waveguide core.

Preferably, the laser waveguide further comprises at least one optical interference mirror.

More preferably, the optical interference mirror is provided at the input of the waveguide. The interference mirror may be butt-coupled to or directly deposited at the input of the waveguide.

The laser waveguide may include two mirrors and a grating. Alternatively, the laser waveguide may include one mirror and two gratings. Alternatively, the laser waveguide may include three gratings. The grating formed may be a Bragg grating. The grating may form an output coupler for said laser waveguide.

The laser waveguide may further comprise an optical interference mirror butt coupled to or directly deposited at the output of the waveguide.

In accordance with a fourth aspect of the invention there is provided method of fabricating a laser waveguide, comprising forming a waveguide according to the method of the second aspect of the invention, the method of fabricating the laser waveguide further including the steps of:

forming at least one grating in said waveguide core.

The method may further include the step of attaching at least one optical interference mirror to the waveguide.

The optical interference mirror may be attached to an input of the waveguide.

The grating may be formed using a laser operating at a wavelength in the range of 150 nm to 400 nm through a phase mask deposited on top of said upper cladding layer of the waveguide. The mask may be a quartz mask. The grating may be formed using a using an interference

side writing technique. The grating may be formed using a direct writing technique. The grating formed may be a Bragg grating.

Preferably, in the above method, the optical interference mirror is butt-coupled to or directly deposited at the input of the waveguide.

The method may further comprise the step of attaching a second optical interference mirror to the output of the waveguide.

DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:-

Figs. 1A to 1C are schematic cross-sectional diagrams of a waveguide with multiple core layers during various stages of fabrication.

Fig. 2A is a schematic representation of a laser waveguide formed from the waveguide shown in Figs. 1A to 1C; and

Fig. 2B is a detail, to an enlarged scale, of the structure shown in Fig. 2A.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings, Figs. 1A to 1C illustrate schematically stages in the fabrication of a waveguide with a multi-layered core according to the invention.

Referring now to Fig. 1A, there is illustrated a waveguide 1 which is fabricated from a substrate 2. The substrate 2 comprises a silicon wafer. However, other suitable substrates including silica and sapphire, may be used.

A silica buffer layer 3, comprising a thermally oxidised layer of the substrate 2, is formed on the substrate 2. The thickness of the buffer layer 3 is 15 μm which lies in a preferred range of 5 μm to 20 μm.

A suitable method, for example, a flame hydrolysis deposition (FHD) method, is used to deposit a first core layer 4 on top of the buffer layer 3. The thickness of the first core layer 4 is 2 μm which lies in a preferred range of 0.2 μm to 30 μm.

The material included in the first core layer 4 provides a high photosensitive response to an optical signal. In a preferred embodiment, the first core layer 4 includes a high concentration of Germanium dopant, for example 17 %wt, co-doped with Boron, for example 5 %wt. Other dopant ions can be included, or a mixture of dopant ions, for example, tin, cerium, and/or sodium.

The dopant and co-dopants are introduced during the deposition of the first core layer 4. The Germanium dopant induces a high photosensitive response and the Boron co-dopant lowers the refractive index induced by the high level of Germanium in the first core layer 4. The concentrations of the dopant and co-dopant are adjusted to 17% wt and 5% wt to give a difference between the refractive index of the first core layer 4 and the refractive index of the buffer layer 3 of 0.75% which lies in a preferred range of 0.05% to 2.0% .

The first core layer 4 is then consolidated by a suitable method, for example by a second pass of the FHD burner or by consolidating the waveguide 1 in an electrical furnace.

Fig. 1B shows a further stage in the fabrication of the waveguide 1 in which a second core layer 5 is formed on the first core layer 4.

The second core layer 5 is deposited on the first core layer 4 using a suitable method, for example FHD, and is then suitably consolidated, for example, in an electrical furnace.

The second core layer 5 is doped with rare earth dopant ions, for example Er^{+3}, using an aerosol doping technique, and co-doped, for example, with Phosphorus during the deposition of the second core layer 5. The thickness of the second core layer 5 is 4μm, which lies in the range of 0.2μm to 30μm.

Alternative methods can be used to dope the second core layer 5 such as solution doping. Preferably, the dopant and co-dopant are simultaneously introduced in a controlled manner during the deposition of the second core layer 5. The concentrations of the dopant and co-dopant can be controlled so that the second core layer 5 provides the desired signal gain for optical signals propagating through the waveguide and also to ensure that the refractive index of the second core layer 5 is matched to the refractive index of the first core layer 4. In this embodiment, the indices are substantially matched. Alternatively, the first core layer 4 and the second core layer 5 can be subjected to a further process, for example, UV trimming, to effect matching of their refractive indices.

The photosensitive response of the first core layer 4 in combination with the optical signal gain of the second core layer 5 effect the overall level of optical signal amplification provided by the waveguide 1.

A waveguide core 6 is then formed from the first core layer 4 and the second core layer 5 by using a suitable method, for example conventional photolithographic and/or reactive ion etching (RIE) methods. A portion of the second core layer 5 is suitably masked and the unwanted portions of the second core layer 5 and the underlying first core layer 4 are etched away to leave the waveguide core 6. The overall dimensions of the waveguide core 6 formed are $6\mu m$ x $6\mu m$ which is in a preferred range of $0.4\mu m$ x $0.4\mu m$ to 60 μm x $60\mu m$.

The co-dopant, here Boron, in the first core layer 4 reduce the refractive index of the waveguide core 6 and enable single mode operation even for large waveguide cores, for example waveguide cores whose dimensions are in the range of $0.4\mu m$ x $0.4\mu m$ to 60 μm x $60\mu m$. The co-dopant in the first core layer 4 can also provide other advantages such as enabling higher refractive index changes to occur during later stages of fabrication of a waveguide with multiple core layers.

The first core layer 4 effectively can reduce the optical signal gain provided by the second core layer 5. It is thus advantageous for the first core layer 4 to be as photosensitive as possible in particular as the refractive index modulation no longer occurs over the entire volume of the waveguide core 6.

Fig. 1C shows a further stage in the fabrication of the waveguide. An upper cladding layer 7 is deposited on the waveguide core 6 using an FHD method. The upper

cladding layer 7 embeds the waveguide core 6. The upper cladding layer 7 is doped during deposition, for example with Phosphorus and Boron, to adjust its refractive index until the refractive index of the upper cladding layer 7 matches the refractive index of the buffer layer 3. The upper cladding layer 7 is then consolidated, for example in an electrical furnace.

In a second preferred embodiment of the invention, a lower cladding layer is formed on top of the buffer layer 3 before the first core layer 4 is deposited and in which the level of dopant in the upper cladding layer 7 is adjusted until the refractive index of the upper cladding layer 7 matches that of the lower cladding layer. The lower cladding layer can be deposited and consolidated using the same techniques as the upper cladding layer 7.

In an alternative layer structure the first core layer 4 may be deposited on top of the second core layer 5 or respective first core layers 4 may be provided both below and on top of the second core layer 5. The core layer 5 is then sandwiched between two photo-sensitive first core layers 4 increasing the coupling coefficient of the device.

It is possible also, for certain applications, to dope the photo-sensitive first core layer 4 with a small amount of rare earth ions.

Referring now to Figs. 2A and 2B of the drawings, there is shown a schematic diagram of laser waveguide according to the invention. Figs. 2A and 2B show a cross-section parallel to the longitudinal axis of the laser waveguide core, such that the waveguide core is seen only in profile.

Fig. 2A shows a planar laser waveguide 10 incorporating a Bragg grating 11. The laser waveguide 10 includes a silicon substrate layer 12 and a silica buffer layer 13 comprising a thermally oxidised layer of the substrate 12. The buffer layer 13 is formed on the substrate layer 12.

Fig. 2B is an enlarged view of a section of Fig. 2A. A first core layer 14 is deposited and consolidated on the buffer layer 13 and second core layer 15 is deposited and consolidated on the first core layer 14 using the techniques described above for the deposition and consolidation of first and second core layers 4 and 5 in the waveguide 1. The first core layer 14 can alternatively be formed on an lower cladding layer (not shown) formed on buffer layer 13.

The second core layer 15 is doped with neodymium instead of the erbium used as a dopant in the second core layer 5. Fig. 2A represents a cross-section through the laser waveguide 10 parallel to the direction of light propagation through the waveguide 10 (i.e., normal to the cross-sectional plane through the waveguide shown in Fig. 1C). The waveguide core 16 is formed from said first core layer 14 and said second core layer 15 using the same technique described above for the formation of the first core layer 4 and the second core layer 15.

An upper cladding layer 17 is then deposited on the second core layer 15 and the grating 11. The upper cladding layer 17 is deposited and consolidated using the same methods as described above for the deposition and consolidation of the upper cladding layer 7 in the fabrication of waveguide 1.

The laser cavity of the laser waveguide 10 is fabricated by writing the Bragg grating 11 into a generally central portion of the first core layer 14 and the second core layer 15. Conventionally, the Bragg grating 11 may be written using a KrF excimer laser operating at 248 nm through a quartz phase mask deposited on top of the upper cladding layer.

An input 18 of the laser waveguide 10 provides an optical signal at a pump wavelength to the laser waveguide 10. An optical interference mirror 19 butt-coupled to the input end 18 of the laser waveguide 10 has a high reflectivity (R_{sig} = 99.9%) around the maxima of the desired output wavelength and has a high transmittance at the pump wavelength (T_{pump} > 95%). The grating 11 forms an output coupler at the output 20 of the laser waveguide 10.

The grating 11 is designed for use at 1050 nm and the reflectivity of the grating 11 formed saturates at 80%. The phase mask used to form the grating 11 has a pitch of 720 nm. In other embodiments, however, it is possible to form gratings 11 which can be used at a wavelength in the range of 500 nm to 2100 nm by using suitable phase masks.

In another embodiment of a laser waveguide, a grating 11 can be provided at both the input 18 and the output 20 of the laser waveguide 10, preferably with both gratings having substantially the same Bragg wavelength thus providing a distributed Bragg reflection laser (DBR).

In yet another embodiment, a distributed feedback laser (DFB) can also be formed by having a grating extending

along the length of the gain cavity formed by the core layer 5.

Further, a multicavity laser can be formed by butt-coupling another mirror to the output end of the laser waveguide 10. These external mirrors can be bulk mirror butt-coupled or mirrors directly deposited on the ends of the waveguide. A multiple wavelength laser can be provided by photoimprinting a sampled grating in the waveguide core, with precise control of channel spacing. Additionally, a multiple wavelength laser can be achieved by exposing the same core area to very similar UV patterns, with each exposure determining each one of the emission wavelengths of the superimposed Bragg gratings. An additional grating can be defined to provide gain equalisation for the several wavelengths.

Thus, a multicavity laser can be constructed by using two mirrors and a grating, one mirror and two gratings, or indeed three gratings.

Still further, in a different application, for example, optical amplifiers, a grating can also be formed on the first core layer 4 to act as a "tap" to flatten optical gain spectra.

While several embodiments of the present invention have been described and illustrated, it will be apparent to those skilled in the art once given this disclosure that various modifications, changes, improvements and variations may be made without departing from the spirit or scope of this invention.